Randomized Algorithms
Part Two
Outline for Today

- **Quicksort**
  - Can we speed up sorting using randomness?

- **Indicator Variables**
  - A powerful and versatile technique in randomized algorithms.

- **Randomized Max-Cut**
  - Approximating \textbf{NP}-hard problems with randomized algorithms.
Quicksort
Partition-Based Selection
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21 32 18 38 17 41 52 53 54 68 70 99 85 98
Partition-Based Selection
Partition-Based Sorting
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Quicksort

- **Quicksort** is as follows:
  - If the sequence has 0 elements, it is sorted.
  - Otherwise, choose a pivot and run a partitioning step to put it into the proper place.
  - Recursively apply quicksort to the elements strictly to the left and right of the pivot.
Initial Observations

• Like the partition-based selection algorithms, quicksort's behavior depends on the choice of pivot.
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    \[
    \begin{align*}
    T(0) &= \Theta(1) \\
    T(n) &= 2T(\lfloor n / 2 \rfloor) + \Theta(n)
    \end{align*}
    \]

    \[T(n) = \Theta(n \log n)\]
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\begin{align*}
T(0) &= \Theta(1) \\
T(n) &= T(n - 1) + \Theta(n)
\end{align*}
\]

\[
T(n) = \Theta(n^2)
\]
Choosing Random Pivots

- As with quickselect, we can ask this question: what happens if you pick pivots purely at random?
- This is called randomized quicksort.
- Question: What is the expected runtime of randomized quicksort?
Accounting Tricks

- As with quickselect, we will *not* try to analyze quicksort by writing out a recurrence relation.
- Instead, we will try to account for the work done by the algorithm in a different but equivalent method.
- This will keep the math a *lot* simpler.
Work done comes from two sources:
1. Work making recursive calls
2. Work partitioning elements.

How much work is from each source?
Counting Recursive Calls

- When the input array has size $n > 0$, quicksort will
  - Choose a pivot.
  - Recurse on the array formed from all elements before the pivot.
  - Recurse on the array formed from all elements after the pivot.
- Given this information, can we bound the total number of recursive calls the algorithm will make?
Counting Recursive Calls

- Begin with an array of $n$ elements.
- Each recursive call deletes one element from the array and recursively processes the remaining subarrays.
- Therefore, there will be $n$ recursive calls on nonempty subarrays.
- Therefore, can be at most $n + 1$ leaf nodes with calls on arrays of size 0.
- Would expect $2n + 1 = \Theta(n)$ recursive calls regardless of how the recursion plays out.
Theorem: On any input of size $n$, quicksort will make exactly $2n + 1$ total recursive calls.

Proof: By induction. As a base case, the claim is true when $n = 0$ since just one call is made. Assume the claim is true for $0 \leq n' < n$. Then quicksort will split the input apart into a piece of size $k$ and a piece of size $n - k - 1$. The first piece leads to at most $2k + 1$ calls and the second to $2n - 2k - 2 + 1 = 2n - 2k - 1$ calls. This gives a total of $2n$ calls, and adding in the initial call yields a total of $2n + 1$ calls. ■
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Counting Partition Work

- From before: running partition on an array of size $n$ takes time $\Theta(n)$.
- More precisely: running partition on an array of size $n$ can be done making exactly $n - 1$ comparisons.
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- From before: running partition on an array of size $n$ takes time $\Theta(n)$.
- More precisely: running partition on an array of size $n$ can be done making exactly $n - 1$ comparisons.
- **Idea:** Account for the total work done by the partition step by summing up the total number of comparisons made.
- Will only be off by $\Theta(n)$ (the -1 term from $n$ calls to partition); can fix later.
Work done comes from two sources:

1. Work making recursive calls
2. Work partitioning elements.

How much work is from each source?

$\Theta(n + \#\text{compares})$
Counting Comparisons

- One way to count up total number of comparisons: Look at the sizes of all subarrays across all recursive calls and sum up across those.

- Another way to count up total number of comparisons: Look at all pairs of elements and count how many times each of those pairs was compared.

- Account “vertically” rather than “horizontally”
Return of the Random Variables

- Let's denote by $v_i$ the $i$th largest value of the array to sort, using 1-indexing.
  - For now, assume no duplicates.
- Let $C_{ij}$ be a random variable equal to the number of times $v_i$ and $v_j$ are compared.
- The total number of comparisons made, denoted by the random variable $X$, is

$$X = \sum_{i=1}^{n} \sum_{j=i+1}^{n} C_{ij}$$
Expecting the Unexpected

- The expected number of comparisons made is $E[X]$, which is

$$E[X] = E\left[ \sum_{i=1}^{n} \sum_{j=i+1}^{n} C_{ij} \right]$$
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$$
E[X] = E\left[ \sum_{i=1}^{n} \sum_{j=i+1}^{n} C_{ij} \right] = \sum_{i=1}^{n} \sum_{j=i+1}^{n} E[C_{ij}]
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(Isn't linearity of expectation great?)
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(Isn't linearity of expectation great?)
When Compares Happen

- We need to find a formula for $E[C_{ij}]$, the number of times $v_i$ and $v_j$ are compared.

- Some facts about partition:
  - All $n - 1$ elements other than the pivot are compared against the pivot.
  - No other elements are compared.
  - Therefore, $v_i$ and $v_j$ are compared only when $v_i$ or $v_j$ is a pivot in a partitioning step.
When Compares Happen

- **Claim**: If $v_i$ and $v_j$ are compared once, they are never compared again.
- Suppose $v_i$ and $v_j$ are compared. Then either $v_i$ or $v_j$ is a pivot in a partition step.
- The pivot is never included in either subarray in a recursive call.
- Consequently, this is the only time that $v_i$ and $v_j$ will be compared.
Defining $C_{ij}$

- We can now give a more rigorous definition of $C_{ij}$:

$$C_{ij} = \begin{cases} 
1 & \text{if } v_i \text{ and } v_j \text{ are compared} \\
0 & \text{otherwise}
\end{cases}$$
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- Given this, $E[C_{ij}]$ is given by

$$E[C_{ij}] = 0 \cdot P(C_{ij} = 0) + 1 \cdot P(C_{ij} = 1)$$
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Our Expected Value

• Using the fact that

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E[C_{ij}] = P(v_i \text{ and } v_j \text{ are compared})
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we have

\[
E[X] = \sum_{i=1}^{n} \sum_{j=i+1}^{n} E[C_{ij}]
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• Amazingly, this reduces to a sum of probabilities!
Indicator Random Variables

- An **indicator random variable** is a random variable of the form

\[ X = \begin{cases} 
1 & \text{if event } \mathcal{E} \text{ occurs} \\
0 & \text{otherwise} 
\end{cases} \]

- For an indicator random variable \( X \) with underlying event \( \mathcal{E} \), \( E[X] = P(\mathcal{E}) \).

- This interacts very nicely with linearity of expectation, as you just saw.

- We will use indicator random variables extensively when studying randomized algorithms.
What is the probability \( v_i \) and \( v_j \) are compared?
Comparing Elements

- **Claim:** $v_i$ and $v_j$ are compared iff $v_i$ or $v_j$ is the first pivot chosen from $v_i, v_{i+1}, v_{i+2}, \ldots, v_{j-1}, v_j$.

- **Proof Sketch:** $v_i$ and $v_j$ are together in the same array as long as no pivots from this range are chosen. As soon as a pivot is chosen from here, they are separated. They are only compared iff $v_i$ or $v_j$ is the chosen pivot.

- **Corollary:**
  \[
P(v_i \text{ and } v_j \text{ are compared}) = \frac{2}{j - i + 1}
  \]
Plugging and Chugging

$$E[X] = \sum_{i=1}^{n} \sum_{j=i+1}^{n} P(v_i \text{ and } v_j \text{ are compared})$$
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Let \( k = j - i \). Then \( k + i = j \), so we can just the loop bounds as

\[ i + 1 \leq j \leq n \]
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i + 1 \leq k + i \leq n
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\[
1 \leq k \leq n - i
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Plugging and Chugging

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\leq \sum_{i=1}^{n} \sum_{k=1}^{n} \frac{2}{k+1}
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\[
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\[
= n \sum_{k=1}^{n} \frac{2}{k+1}
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Harmonic Numbers

• The $n$th **harmonic number**, denoted $H_n$, is defined as

$$H_n = \sum_{i=1}^{n} \frac{1}{i}$$

• Some values:
  - $H_0 = 0$  
  - $H_1 = 1$  
  - $H_2 = \frac{3}{2}$  
  - $H_3 = \frac{11}{6}$  
  - $H_4 = \frac{25}{12}$  
  - $H_5 = \frac{137}{60}$
Mathematical Harmony

• **Theorem:** $H_n = \Theta(\log n)$

• **Proof Idea:**
Mathematical Harmony

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![Graph showing the relationship between $H_n$ and $\frac{1}{x}$]
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$$H_n \leq 1 + \int_1^n \frac{dx}{x} = \ln n + 1$$
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\[
\ln(n+1) \leq H_n \leq \ln n + 1
\]
The Finishing Touches

\[ E[X] \leq 2n \sum_{k=1}^{n} \frac{1}{k} \]
The Finishing Touches

\[ E[X] \leq 2n \sum_{k=1}^{n} \frac{1}{k} = 2n \cdot H_n \]
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\[ E[X] \leq 2n \sum_{k=1}^{n} \frac{1}{k} = 2n \cdot H_n = 2n \cdot \Theta(\log n) \]
The Finishing Touches

\[
E[X] \leq 2n \sum_{k=1}^{n} \frac{1}{k} = 2n \cdot H_n = 2n \cdot \Theta(\log n) = O(n \log n)
\]
Why This Matters

- We have just shown that the runtime of randomized quicksort is, on expectation, $O(n \log n)$.
- To do so, we needed to use two new mathematical techniques:
  - Indicator random variables.
  - Bounding summations by integrals.
- We will use the first of these techniques more extensively over the next few days.
Introsort

- As with quickselect, quicksort still has a pathological $\Theta(n^2)$ case, though it's unlikely.
- Quicksort is, on average, faster than heapsort.
- The introsort algorithm addresses this:
  - Run quicksort, tracking the recursion depth.
  - If it exceeds some limit, switch to heapsort.
- Given good pivots, runs just as fast as quicksort.
- Given bad pivots, is only marginally worse than heapsort.
- Guarantees $O(n \log n)$ behavior.
A Different Algorithm: Max-Cut
Global Cuts
Global Cuts
Global Cuts
Global Cuts
Global Cuts
Global Cuts
Global Cuts
Global Cuts

• Given an undirected graph $G = (V, E)$, a cut in $G$ is a pair $(S, V - S)$ of two sets $S$ and $V - S$ that split the nodes into two groups.

• The size or cost of a cut, denoted by $c(S, V - S)$, is the number of edges with one endpoint in $S$ and one in $V - S$.

• A global min cut is a cut in $G$ with the least total cost. A global max cut is a cut in $G$ with maximum total cost.
Global Cuts

• Interestingly:
  • There are many polynomial-time algorithms known for global min-cut.
  • Global max-cut is \textbf{NP}-hard and no polynomial-time algorithms are known for it.
• Today, we'll see an algorithm for approximating global max-cut.
• On Friday, we'll see a randomized algorithm for finding a global min-cut.
Approximating Max-Cut

- For a maximization problem, an **$\alpha$-approximation algorithm** is an algorithm that produces a value that is within a factor of $\alpha$ of the true value.

- A 0.5-approximation to max-cut would produce a cut whose size is at least 50% the size of the true largest cut.

- Our goal will be to find a randomized approximation algorithm for max-cut.
A Really Simple Algorithm

• Here is our algorithm:
  • For each node, toss a fair coin.
  • If it lands heads, place the node into one part of the cut.
  • If it lands tails, place the node into the other part of the cut.
Analyzing the Algorithm

• On expectation, how large of a cut will this algorithm find?

• For each edge $e$, $C_e$ be an indicator random variable where

$$C_e = \begin{cases} 1 & \text{if } e \text{ crosses the cut} \\ 0 & \text{otherwise} \end{cases}$$

• Then the number of edges $X$ crossing the cut will be given by

$$X = \sum_{e \in E} C_e$$
What Did You Expect?

• The expected number of edges crossing the cut is given by $E[X]$.

• This is

$$E[X] = E\left[ \sum_{e \in E} C_e \right]$$
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= \sum_{e \in E} E[C_e]
= \sum_{e \in E} P(e \text{ crosses the cut})
$$
Four Possibilities
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That Was Unexpected

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• All cuts have size $\leq m$, so this is always within a factor of two of optimal!
Randomized Approximation Algorithms

• This algorithm is a randomized 0.5-approximation to max-cut.
• The algorithm runs in time $O(n)$. 
• It's $\textbf{NP}$-hard to find a true maximum cut, but it's not at all hard to (on expectation) find a cut that has size at least half that of the maximum cut!
Improving the Odds

- Running our algorithm will, on expectation, produce a cut with size \( m / 2 \).
- However, we don't know the actual probability that our cut has this size.
- We can use a standard technique to amplify the probability of success.
Do it Again

• Since any *individual* run of the algorithm might not produce a large cut, we could try this approach:
  • Run the algorithm $k$ times.
  • Return the largest cut found.
• Goal: Show that with the right choice of $k$, this returns a large cut with high probability.
  • Specifically: Will show we get a cut of size $m / 4$ with high probability.
• Runtime is $O((m + n)k)$: $k$ rounds of doing $O(m + n)$ work ($n$ to build the cut, $m$ to determine the size.)
More Probabilities

• Let $X_1, X_2, \ldots, X_k$ be random variables corresponding to the sizes of the cuts found by each run of the algorithm.
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- Let $\mathcal{E}$ be the event that our algorithm produces a cut of size less than $m/4$. Then

$$\mathcal{E} = \bigcap_{i=1}^{k} \left( X_i \leq \frac{m}{4} \right)$$
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A Simplification

• Let $Y_1, Y_2, \ldots, Y_k$ be random variables defined as follows:

$$Y_i = m - X_i$$

• Then

$$P(\mathcal{E}) = \prod_{i=1}^{k} P(X_i \leq \frac{m}{4}) = \prod_{i=1}^{k} P(Y_i \geq \frac{3m}{4})$$

• What now?
Markov's Inequality

• **Markov's Inequality** states that for any nonnegative random variable $X$, that

$$P(X \geq c) \leq \frac{E[X]}{c}$$

• Equivalently:

$$P(X \geq cE[X]) \leq \frac{1}{c}$$

• This holds for any random variable $X$.

• Can often get tighter bounds if we know something about the distribution of $X$. 
Markov to the Rescue

• Let $Y_1, Y_2, \ldots, Y_k$ be random variables defined as follows:

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Markov to the Rescue

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• Then
  \[
P(\mathcal{E}) = \prod_{i=1}^{k} P(Y_i \geq \frac{3m}{4}) \leq \prod_{i=1}^{k} \frac{E[Y_i]}{3m/4}\]
Markov to the Rescue

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- Then
  $$P(\mathcal{E}) = \prod_{i=1}^{k} P(Y_i \geq \frac{3m}{4}) \leq \prod_{i=1}^{k} \frac{E[Y_i]}{3m/4}$$
  $$= \prod_{i=1}^{k} \frac{m/2}{3m/4} = \prod_{i=1}^{k} 2/3 = \left(\frac{2}{3}\right)^k$$
The Finishing Touches

- If we run the algorithm $k$ times and take the maximum cut we find, then the probability that we don't get $m / 4$ edges or more is at most $(2 / 3)^k$.

- The probability we do get at least $m / 4$ edges is at least $1 - (2 / 3)^k$.

- If we set $k = \log_{3/2} m$, the probability we get at least $m / 4$ edges is $1 - 1 / m$.

- There is a randomized, $O((m + n) \log m)$-time algorithm that finds a (0.25)-approximation to max-cut with probability $1 - 1 / m$. 
Why This Works

- Given a randomized algorithm that has a probability \( p \) of success, we can amplify that probability significantly by repeating the algorithm multiple times.

- This technique is used extensively in randomized algorithms; we'll see another example of this on Friday.
Next Time

- Karger's Algorithm
- Finding a Global Min-Cut
- Applications of Global Min-Cut